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SOME PECULIARITIES IN THE DESIGN OF A NONEQUILIBRIUM TWO-STEP NOZZLE

by
V. A. Bashkatov
A. A. Tsvetkova

Akademiia Nauk SSSR, Sibirskoe Otdelenie, Izvestiia, Seriia Tekhnicheskikh Nauk, 6, No. 2, 88-93 (1965)

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The existing literature which is concerned with various parameters (Fuks[1], Lyshevskii[2], Vyrubov[3], and others) examines problems of acceleration and inhibition of droplets in a gas flow. Also known are investigations of thermal and "expendable" influence (effect) on gas flow during evaporation and appearance of droplets by condensation[4]. In the solution of those problems the mechanical interaction between the gas and droplets was not considered.

Kh. A. Khassan in his investigations[5], 1964, used a successive approximation method for solving the problem on thermal and mechanical interaction between solid particles and a gas flow. The particle dynamic equation in this study was made by a linear (Stokes) approximation without the pressure gradient which significantly limits the application area of this method.

This article examines the gas flow and droplets, the temperature and velocity of which are essentially different; therefore, the thermal and mechanical interaction is considered and the droplet dynamics equation is made in form of a quadratic law where the pressure gradient is also considered.

As presented in this article the problem is useful for instances appearing frequently in the technology, and will satisfy within the following limitations:

1. The lines of the flow change smoothly, the channel length is greater than the width; suitable one-dimensional approximation.

2. No chemical and phase changes.

3. Number of droplets occuring in 1 kg. of gas, their dimensions, and the parameters of the gas are such that the following inequality is formed:

$$2d_k < l \ll L, \tag{1}$$

where

d_k - statistical mean diameter of the droplet by weight,
l - statistical mean distance between the droplets,
L - linear dimension of total flow.

4. The thermal conductivity of the liquid is high; therefore, it is assumed that the droplet temperature is distributed equally.

5. The gas velocity with respect to the droplet should be subsonic. The following assumptions are used for the composition and solution of the equations:

a) the probability of a break-up and collision of the droplets is negligible; all the droplets of uniform dimensions are equal by weight according to their statistical mean (d_k);

b) the mechanical interaction between the gas and droplets occurs in form of an elastic impact; dissipation of energy during this process is insignificant.

According to the inequality (1) a small volume contains a large number of droplets with respect to the total flow. The gas and droplet parameters in this volume are uniform in size and change smoothly in the direction of flow. Disturbances in the gas flow caused by the interaction with each droplet will level off in a short interval. Therefore the gas parameters may be averaged for a small volume (element) integrating all droplets affecting the flow. This is equivalent to considering a volumetric force of interaction with droplets, and the heat capacity of droplets in the volume (P_k, Q).

For calculation of that process we will use separate equations for each phase.

Equation of the gas flow dynamics:

$$\rho w \frac{dw}{dx} + \frac{dp}{dx} = \dot{P}_k . \tag{2}$$

This equation may be used here as an extension of the Bernoulli equation:

$$wdw + \frac{1}{\rho} dp = \frac{1}{\rho} P_k dx = gdL. \tag{2a}$$

Equation of the first element for gas in motion for a stationary coordinate system:

$$dQ = dI + Ad\left(\frac{w^2}{2g}\right) + AdL. \tag{3}$$

Equation of state:

$$p = \rho RTg. \tag{4}$$

Equation of discontinuity:

$$\frac{G}{g} = F\rho w = F_0\rho_0 w_0 ; \quad \frac{G_\ell}{g} = S\rho_\ell u = S_0\rho_\ell u_0 . \tag{5}$$

Equation of the droplet dynamics:

$$\left(\mu_x + 1\right) m_k \frac{du}{d\tau_k} = \frac{C_k \Omega_k}{2} \rho (w - u)^2 - v_k \frac{dp}{dx_k} \tag{6}$$

Equation of the droplet heat balance:

$$a\Omega_k \left(T - T_k\right) = m_k g C_k \frac{dT_k}{d\tau} . \tag{7}$$

Considering that

$$dQ = -\mu C_k dT_k , \tag{8}$$

$$dL = \frac{\mu}{g} udu, \tag{9}$$

$$dI = C_p dT, \tag{10}$$

and normalizing the sought functions at their initial values we obtain:

$$Bt'_k + \frac{1}{(k-1) M_0^2} t'_r + \overline{w}\,\overline{w}' + \mu\varphi_0^2 \overline{u}\,\overline{u}' = 0 ; \tag{11}$$

$$\frac{1}{kM_0^2} \cdot \frac{\overline{p}'}{\rho} + \overline{w}\,\overline{w}' + \mu\varphi_0^2 \overline{u}\,\overline{u}' = 0 ; \tag{12}$$

$$\overline{p} = \overline{\rho} t_r ; \tag{13}$$

$$\overline{w}\,\overline{\rho}\,\overline{F} = 1 ; \tag{14}$$

$$t'_k = C\left(t_r - \frac{T_{k0}}{T_0} t_k\right) \frac{1}{\overline{u}} ; \tag{15}$$

$$u_0 \overline{u} = \frac{dx_k}{d\tau} ; \tag{16}$$

$$\bar{S}\,\bar{u} = 1; \tag{17}$$

$$\frac{\rho_\ell}{\rho_0} \cdot \varphi_0^2\, \bar{u}\, \bar{u}' = 3\, \frac{C_x}{d_k}\, \bar{\rho}\left(\bar{w} - \varphi_0 \bar{u}\right)^2 - \frac{1}{kM_0^2}\, \bar{p}' \tag{18}$$

The following symbols were introduced in the Equations (2) - (17):

$$B = \frac{\mu C_k}{AR} \cdot \frac{1}{kM_0^2} \cdot \frac{T_{k0}}{T_0} \quad ;$$

$$C = \frac{6\alpha}{d_k g\, \rho_\ell\, u_0\, C_k} \cdot \frac{T_0}{T_{k0}} \; ;$$

$$\varphi_0 = \frac{u_0}{w_0} \; ; \quad \mu = \frac{G_\ell}{G} \; ; \quad \bar{w} = \frac{w}{w_0} \; ; \quad \bar{u} = \frac{u}{u_0} \; ; \; t_r = \frac{T}{T_0} \; ; \quad t_k = \frac{T_k}{T_{k0}}$$

$w, p, T, \rho, F, R, k, C_p, M$ - velocity, pressure, temperature, density, cross section, gas constant, adiabatic indicator, heat capacity at a constant pressure, and the Mach number of a gas flow;

$u, \rho_\ell, T_k, C_k,$ - velocity, density, temperature and heat capacity of the liquid phase (droplet);

S - cross section of the flow taken by the liquid phase;
m_k, v_k, Ω_k, d_k - mass, volume, surface and the droplet diameter;
C_x - coefficient of the resistance;
α - heat transfer coefficient from gas to droplet;
$(\;)'$ - derivative by x;
μ_x - coefficient of additional mass;

$$A = (421)^{-1} \quad \frac{\text{kcal.}}{\text{kg.}\cdot\text{mass}} \; ;$$

$$g = 9.81 \text{ m/sec}^2 \; ;$$

x_k - coordinate of the droplet at a moment of time τ_k.

The following unknowns are in the system (11) - (18): $\bar{w}, \bar{u}, t_r, \bar{\rho}, \bar{p}, t_k, x_k, \bar{S}$. The initial conditions : at $\tau_k = 0$, $x_k = 0$, $\bar{w} = \bar{u} = t_r = t_k = \bar{p} = \bar{\rho} = \bar{S} = 1$.

The above mentioned coefficients should be used for the solution, also the $\overline{F}(x)$ or any other unknown function. If the parameters change over a large range the coefficients C_x, α, C_p, and k are variables.

Generally the solution of the system (11) - (18) is obtained numerically. In the isobaric and isochoric process, when $\overline{F}(x)$ must be such that it will satisfy $\overline{p} = 1$ or $\overline{\rho} = 1$, certain functions are found to be in a terminal form or in the quadratures (19) - (29).

The isobaric process

$$\overline{w}^2 = 1 - \mu \varphi_0^2 \left(\overline{u}^2 - 1\right); \tag{19}$$

$$t_k = \frac{T_0}{T_{k0}\left[B(k-1)M_0^2 \dfrac{T_0}{T_{k0}} + 1\right]} \left\{ B(k-1)M_0^2 + 1 + \right.$$

$$\left. + \exp \frac{6\alpha\left[B(k-1)M_0^2 \dfrac{T_k}{T_{k0}} + 1\right]}{C_k \cdot \rho_\ell \cdot g \cdot d_k} \cdot \tau \right\}; \tag{20}$$

$$t_r = 1 - B(k-1)M_0^2 \left(t_k - 1\right); \tag{21}$$

$$\int_t^{\overline{u}} \frac{d\overline{u}}{\left[\sqrt{1 - \mu\varphi_0^2\left(\overline{u}^2 - 1\right)} - \varphi_0 \overline{u}\right]^2} = \frac{C_k \cdot g \cdot u_0 \cdot C_x \cdot \rho_0}{2\alpha\varphi_0^2\left[B(k-1)M_0^2 + 1\right]} \quad X$$

$$X \ln \frac{\exp \dfrac{6\alpha\left[B(k-1)M_0^2 \dfrac{T_0}{T_{k0}} + 1\right]}{C_k \cdot \rho_\ell \cdot g \cdot d_k} \cdot \tau}{\dfrac{B(k-1)M_0^2 + 1}{B(k-1)M_0^2} \cdot \dfrac{T_{k0}}{T_0} - \exp \dfrac{6\alpha\left[B(k-1)M_0^2 \dfrac{T_0}{T_{k0}} + 1\right]}{C_k \cdot \rho_\ell \cdot g \cdot d_k} \cdot \tau} : \tag{22}$$

$$x_k = u_0 \int_0^\tau \overline{u}\, d\tau; \tag{23}$$

$$\bar{\rho} = \frac{1}{\bar{t}_r} \quad ; \tag{24}$$

$$\bar{S} = \frac{1}{\bar{u}} \quad ; \tag{25}$$

$$\bar{F} = \frac{1}{\bar{w}\,\bar{\rho}} \quad . \tag{26}$$

The isochoric process

$$\left(\bar{w}^2 - 1\right) + \mu\varphi_0^2\left(\bar{u}^2 - 1\right) = 2y \;; \tag{27}$$

$$t_r = 1 - k M_0^2 y \;; \tag{28}$$

$$t_k = 1 + \frac{1}{B(k-1)}\, y \;; \tag{29}$$

$$\frac{\rho_\ell}{\rho_0}\cdot\varphi_0^2\cdot\frac{\bar{u}^2}{2} = 3\,\frac{C_x}{d_k}\int_0^\tau\left[\sqrt{1 + 2y - \mu\varphi_0^2\left(\bar{u}^2 - 1\right)} - \varphi_0\bar{u}\right]^2 d\tau + y; \tag{30}$$

$$y = B(k-1)\,\frac{1 - \dfrac{T_{k0}}{T_0}}{B_k(k-1)M_0^2 + \dfrac{T_{k0}}{T_0}}\left[1 - \exp\left\{-\frac{B_k(k-1)M_0^2 + \dfrac{T_{k0}}{T_0}}{\dfrac{C_k\cdot g\cdot\rho_\ell\cdot d_k}{6a}\cdot\dfrac{T_{k0}}{T_0}}\,\tau\right\}\right];$$

(31)

$$x_k = u_0\int_0^\tau \bar{u}\,d\tau \;; \tag{32}$$

$$\bar{p} = t_r \;; \tag{33}$$

$$\bar{S} = \frac{1}{\bar{u}} \quad ; \tag{34}$$

$$\bar{F} = \frac{1}{\bar{w}} \quad . \tag{35}$$

Figures 1, 2, and 3 show results of the isochoric process calculation to illustrate the influence of the relative flow rate (μ), the droplet dimension $\left(d_k\right)$, the initial conditions of the droplet heating period, and the leveling-off rate of the velocities. Using an electronic computer, a calculation was made for the water vapor, where the water had constant values throughout the process $C_x = 0.62$; $k = 1.3$;

$R = 47 \dfrac{\text{kg. mass}}{\text{kg. }^\circ}$, and initial values of $T_{k0} = 290°K$, $T_{r0} = 2100°K$,

$p_0 = 2\text{atm}$ and $u_0 = 50 \dfrac{m}{sec}$, $w_0 = f(M_0)$ when the vapor first appeared,

that is, at the very moment when the temperature of the droplet reached the temperature of saturation at a local pressure.

In Jenkins' work[6] the deformation of the droplet was considered by the selection of the value C_x.

Completion of the inequality (1) was controlled by estimating the distance (l) between the droplets using equation

$$l \cong d_k \sqrt[3]{\frac{\pi}{6} \cdot \frac{\rho_\ell}{\rho} \cdot \frac{1}{\mu}} . \tag{36}$$

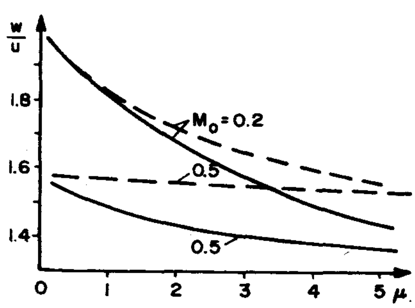

Figure 1

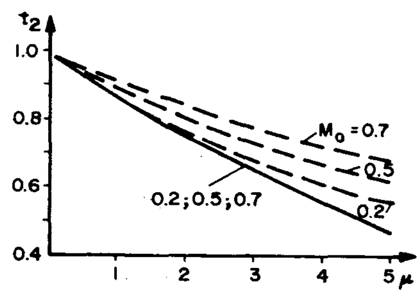

Figure 2

For analyzed examples $l > 3d_k$ in all cross sections. Figures 1 and 2 show the dependence of the gas temperature and relations between the velocities of phases, corresponding to the beginning of evaporation, from the relative flow rate (μ). Figure 3 shows the dependence of the coordinate point, where evaporation begins, from μ. The dashed curves indicate droplets of 500 micra in diameter; the continuous curves, 50 micra in diameter. All the dependencies are shown for the two initial Mach numbers (0.2; 0.5).

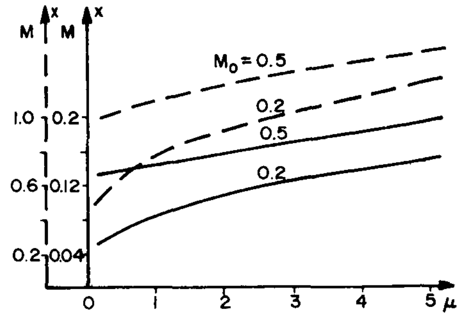

Figure 3

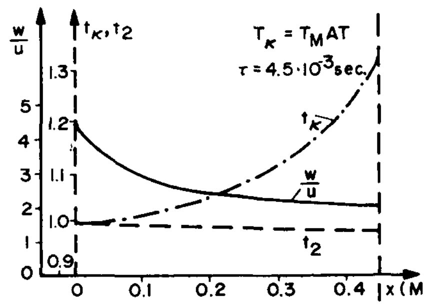

Figure 4

Figure 4 shows changes of temperatures and velocities in the direction of flow in order to illustrate the characteristic of the flow process at $M_0 = 0.2$ and $\mu = 0.1$. The calculation results indicate the wide range of possible values that are characteristic of the gas dynamic process that depends upon the above discussed conditions of its flow (d_k, μ, M_0 and others) prior to the beginning of the phase changes.

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Discussion of the acceleration of droplets in a gas flow, in the case in which the temperature and velocity of the droplets and the gas differ widely. A solution of the problem is obtained by taking the thermal and mechanical interaction between the droplets and the gas into account and using an equation for the droplet dynamics in the form of an empirical quadratic law with allowance for a pressure gradient.

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